

MOLECULAR GAS IN YOUNG DEBRIS DISKS

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ABSTRACT

Gas-rich primordial disks and tenuous gas-poor debris disks are usually considered as two distinct evolutionary phases of the circumstellar matter. Interestingly, the debris disk around the young main-sequence star 49 Ceti possesses a substantial amount of molecular gas, and possibly represents the missing link between the two phases. Motivated to understand the evolution of the gas component in circumstellar disks via finding more 49 Ceti-like systems, we carried out a CO $J=3-2$ survey with Atacama Pathfinder EXperiment, targeting 20 infrared-luminous debris disks. These systems fill the gap between primordial and old tenuous debris disks in terms of fractional luminosity. Here we report on the discovery of a second 49 Ceti-like disk around the 30 Myr old A3-type star HD21997, a member of the Columba Association. This system was also detected in the CO(2–1) transition, and the reliable age determination makes it an even clearer example of an old gas-bearing disk than 49 Ceti. While the fractional luminosities of HD21997 and 49 Ceti are not particularly high, these objects seem to harbor the most extended disks within our sample. The double-peaked profiles of HD21997 were reproduced by a Keplerian disk model combined with the LIME radiative transfer code. Based on their similarities, 49 Ceti and HD21997 may be the first representatives of a so far undefined new class of relatively old ($\gtrsim 8$ Myr), gaseous dust disks. From our results, neither primordial origin nor steady secondary production from icy planetesimals can unequivocally explain the presence of CO gas in the disk of HD21997.

Subject headings: circumstellar matter — infrared: stars — stars: individual (HD21997)

1. INTRODUCTION

Most young stars are surrounded by circumstellar disks, the natural by-product of star formation. After a protostar has formed, its disk plays a crucial role in the evolution of the system, first by serving as reservoir for mass accretion, and later by becoming the birthplace of the planetary system. At early evolutionary stage the mass of the *primordial disk* is dominated by gas, with a few percent of mass in small dust grains. The gaseous component plays an important role in controlling the dust dynamics in the disk (Beckwith et al. 2000), and its dispersal determines the time available to form Jupiter- and Saturn-like giant planets. As the disk evolves, the gas content is removed by viscous accretion (Lynden-Bell & Pringle 1974) and/or by photoevaporation (e.g., Alexander et al. 2006).

Current observational results imply that the primordial gas becomes largely depleted in the first 10 Myr (Zuckerman et al. 1995; Pascucci et al. 2006; Fedele et al. 2010). A gas-poor disk appears, where the

lifetime of individual dust grains under the influence of radiative forces – without the stabilization effect of the surrounding gas – is far less than the stellar age. The dust grains are believed to be continuously replenished by collisions and/or evaporation of previously formed planetesimals (Wyatt 2008, and references therein). In these *debris disks* only a small amount of gas is expected. Similarly to the dust, this gas could be *second generation*, produced by sublimation of planetesimals, photodesorption from dust grains (Grigorieva et al. 2007), or vaporization of colliding dust particles (Czechowski & Mann 2007).

So far only a few debris disks are known with detectable gas component. The edge-on orientation of the disk around β Pic allowed the detection of a very small amount of circumstellar gas ($N_{\text{CO}} \sim 6 \times 10^{14} \text{ cm}^{-2}$) through the presence of absorption/emission lines (Roberge et al. 2000; Brandeker et al. 2004). Redfield (2007) successfully exploited the favorable edge-on geometry of the disk around HD32297 to detect gas via Na I. In contrast to the disks mentioned above, the debris disk around the young main-sequence star 49 Ceti seems to have substantial ($\sim 13 M_{\oplus}$) molecular gas (Zuckerman et al. 1995; Dent et al. 2005; Hughes et al. 2008). The origin of the gas in the above mentioned systems is currently under debate. It can be residual primordial gas that survived longer in the outer disks than usually assumed (Krivov et al. 2009) or it may have formed or been released recently. Based on dynamical arguments, Fernández et al. (2006) suggested that the gas in β Pic is secondary. Analyzing high-resolution data obtained with the SMA interferometer at 230 GHz, Hughes et al. (2008) proposed that 49 Ceti is in a late

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stage of its evolution, possibly representing the link between gas-rich primordial disks and gas-poor optically thin debris disks. Rhee et al. (2007) suggested an age of 20 Myr for 49 Ceti, while Thi et al. (2001) derived ~ 8 Myr as the age of the star. In the case of the older age, 49 Ceti would challenge the current picture of gas disk evolution, while the lower value could still be marginally consistent with a primordial disk phase. The confirmation of the existence of debris disks containing a significant amount of gas would require to find and study more 49 Ceti-like systems with reliable age estimates. It might well be possible that a number of similar systems exists, since most debris disks that are similar to 49 Ceti in terms of age and fractional luminosity have never been observed in molecular lines (most such candidates are in the southern hemisphere). Motivated by this fact, we carried out a survey with the APEX⁸ radio telescope to detect molecular gas in 20 infrared-luminous debris disks. Here we review the results of this survey and report on the discovery of a second 49 Ceti-like disk around the 30 Myr-old star HD21997.

2. SAMPLE DESCRIPTION

For candidate selection we adopted the 49 Ceti system as a template. This A1-type star harbors a dusty disk that re-emits a fraction $f_{\text{dust}} \sim 8 - 9 \times 10^{-4}$ of the star's radiation at infrared wavelengths. This fractional luminosity is an order of magnitude lower than the corresponding value in primordial disks. We used the following target selection criteria: (1) spectral type between A0 and F6; (2) f_{dust} in the range of 5×10^{-4} to 5×10^{-3} that excludes both primordial disks and very tenuous debris disks; (3) the excess emission is confirmed by an instrument independent of *IRAS* (4) ages between 10 and 100 Myr, the age estimate is based on kinematic group membership or other reliable dating methods. In total, 20 candidates were selected from the lists of Chen et al. (2005) and Moór et al. (2006, 2011). Their basic properties are given in Table 1.

For most sources, disk parameters (temperature, radius, and fractional luminosity) were adopted from the literature (Table 1). In all cases, disk radii were estimated by adopting blackbody-like dust emission. For HD121617 no previous literature data were found, thus we collected infrared photometry from the *IRAS* FSC, *AKARI* IRC, *AKARI* FIS and *WISE* (Wright et al. 2010). For HD21997, we also compiled a new spectral energy distribution based on literature data and our own photometry derived from archival observations obtained with the Multiband Imaging Photometer for Spitzer (see Figure 1, 55.3 ± 2.2 mJy at $24 \mu\text{m}$ and 662 ± 47 mJy at $70 \mu\text{m}$; for the description of the processing see Moór et al. 2011). Disk parameters for these two targets were derived following Moór et al. (2011). For sources where submillimeter observations were available, we computed dust masses assuming optically thin emission with $\kappa_{870 \mu\text{m}} = 2 \text{ cm}^2 \text{ g}^{-1}$ and $\beta = 1$ (Nilsson et al. 2010), and dust temperature from Table 1. For comparison of the fundamental parameters, 49 Ceti is also added to Table 1.

⁸ This publication is based on data acquired with the Atacama Pathfinder EXperiment (APEX). APEX is a collaboration between the Max-Planck-Institut für Radioastronomie, the European Southern Observatory, and the Onsala Space Observatory.

3. OBSERVATIONS AND DATA REDUCTION

Our survey was carried out with the APEX 12 m telescope (Güsten et al. 2006) in service mode, between 2008 October and 2009 November. All objects were observed at the 345.796 GHz ^{12}CO $J=3-2$ line using the SHeFI/APEX2 receiver (Vassilev et al. 2008). One source, HD21997 was also observed in the $J=2-1$ transition of ^{12}CO (at 230.538 GHz) with the SHeFI/APEX1 receiver. For the backend, we used the Fast Fourier Transform Spectrometer with 2048 channels providing a velocity resolution of 0.42 and 0.64 km s^{-1} in the $J=3-2$ and $J=2-1$ transitions, respectively. An on-off observing pattern was utilized with beam switching. The total on-source integration time for most sources ranged between 10 and 30 minutes. For HD21997, we integrated longer for a better characterization of the line profile. The weather conditions were generally dry, the precipitable water vapor was below 1.3 mm for most of the $J=3-2$ observations and ranged between 1.3 and 2.7 mm during the $J=2-1$ measurements. The data reduction was performed using the GILDAS/CLASS package⁹. For the final average spectrum, we omitted noisy scans and a linear baseline was subtracted from each individual scan.

4. RESULTS AND ANALYSIS

Among the 20 targets, one system, HD21997, was detected at $>5\sigma$ level in both CO lines. Figure 2 shows the baseline-corrected CO profiles for HD21997. Both lines display double peaked line profile with identical peak positions. The central velocities of both lines are consistent with the systemic velocity of the star ($+17.3 \pm 0.8 \text{ km s}^{-1}$; Kharchenko et al. 2007). We integrated the intensities/fluxes over an interval of 8 km s^{-1} that covers the whole line profile. The beam efficiencies and Kelvin-to-Jansky conversion factors were taken from the APEX web page¹⁰. For the non-detected sources, upper limits were estimated as $T_{\text{rms}} \Delta v \sqrt{N}$, where T_{rms} is the measured noise, Δv is the velocity channel width, and N is the number of velocity channels over an interval of 10 km s^{-1} . The total mass (or upper limit) of CO molecules (M_{CO}) was estimated assuming optically thin emission and local thermodynamic equilibrium (LTE). The excitation temperature (T_{ex}) was assumed to be equal to the dust temperature in Table 1 (i.e., gas and dust are sufficiently coupled). The obtained line intensities/fluxes as well as the estimated CO masses are listed in Table 1. Note that for HD21997 the CO masses computed independently from the (2-1) and (3-2) transitions are significantly different.

Figure 3(left panel) shows the integrated CO(3-2) fluxes and upper limits, normalized to 100 pc, plotted against the fractional luminosities of the disks. For comparison, additional protoplanetary/debris disks around A0-F6-type pre-main/main-sequence stars, including 49 Ceti, are also displayed (Dent et al. 2005; Greaves et al. 2000a,b). Our observations fill the gap between Herbig Ae/Be disks and older debris disks. Note that the fractional luminosities of HD21997 and 49 Ceti are modest even within the debris sample, and significantly lower than those of the primordial disks. Thus,

⁹ <http://iram.fr/IRAMFR/GILDAS/>

¹⁰ <http://www.apex-telescope.org/telescope/efficiency/>

f_{dust} does not appear to be a good proxy for the presence of CO gas in debris disks. Figure 3(right panel) presents the integrated CO(3–2) fluxes versus the (blackbody) radii of the dust disks. Interestingly, the two definite detections, HD21997 and 49 Ceti, harbor the most extended disks, suggesting that large radius and low dust temperature may be essential for CO detection. Although the radii in this analysis rely on the assumption of blackbody grains, the conclusion holds in the case of realistic grain size distributions. Using the blackbody assumption, we may systematically underestimate the true radius, due to the presence of inefficiently emitting small particles. However, assuming similar grains in all disks, the relative distribution of disk radii would not differ from the blackbody case (see e.g., Wyatt 2008).

HD21997 is an A3-type star at a distance of 72 pc (van Leeuwen 2007), a member of the ~ 30 Myr old Columba group (Moór et al. 2006; Torres et al. 2008). Fitting an ATLAS9 atmosphere model (Castelli & Kurucz 2003) to the optical and near-IR (*Hipparcos*, *Tycho-2*, *Two Micron All Sky Survey*) data, assuming solar metallicity and $\log g = 4.25$ yields $T_{\text{eff}} = 8300$ K. The evolutionary tracks of Siess et al. (2000) imply a stellar mass of $1.85 M_{\odot}$. We modeled the measured line profiles of HD21997 with a simple disk geometry assuming a combination of a radial power-law and a vertical Gaussian profile for the density distribution:

$$n_{\text{CO}}(r, z) = n_{\text{CO, in}}(r/R_{\text{in}})^{-\alpha} e^{-z^2/2H^2}. \quad (1)$$

We fixed the following parameters: $H = 0.1r$, $\alpha = -2.5$, $R_{\text{in}} = 63$ AU (Table 1), and $R_{\text{out}} = 200$ AU (typical for Herbig Ae/Be disks; Panić & Hogerheijde 2009). We assumed an H_2 abundance relative to CO of 10^4 , and that gas and dust grains – the latter act like blackbody – are well mixed, prescribing that the gas kinetic temperature and dust temperature distributions are identical. The velocity of the material in the disk was derived by assuming Keplerian orbits around a star of $1.85 M_{\odot}$ mass. Then the CO level populations at each disk position, and the resulting emission line profiles were calculated using the non-LTE spectral line radiation transfer code LIME (Brinch & Hogerheijde 2010). First, we fitted the (3–2) line by adjusting $n_{\text{CO, in}}$ and the disk inclination. The best-fitting model spectrum with $n_{\text{CO, in}} = 10 \text{ cm}^{-3}$ and $i = 45^\circ$ is overplotted with dashed line in Figure 2. With the same parameters we also computed a CO (2–1) profile. As Figure 2 shows, this model significantly underestimates the observed CO(2–1) feature. The reason for this discrepancy is the same as what causes the difference in the CO mass estimates from (2–1) and (3–2) lines: the ratio of integrated CO(3–2) flux to the integrated CO(2–1) flux is only 1.43 ± 0.37 , significantly lower than the ratio of 3.8, expected for $T_{\text{ex}} \sim 60$ K in LTE condition. This low line flux ratio corresponds to an excitation temperature of 13.1 ± 2.7 K. This is unrealistically low (subthermal) for being an LTE value, suggesting that the density of collision partners (H_2) is lower than the critical density, and the excitation is not collisionally dominated. In order to provide a model that can fit both lines simultaneously, we gradually decreased the H_2/CO abundance ratio and repeated the above-mentioned modeling process. We found that with $\text{H}_2/\text{CO} = 1000 \pm 500$, $n_{\text{CO, in}} = 22 \pm 5 \text{ cm}^{-3}$, and $i = 45_{-10}^{+15}$, both line profiles

can be fitted (solid line in Figure 2). Note that in this non-LTE model the kinetic and excitation temperatures of the gas are different. The total CO mass predicted by this model is $M_{\text{CO}} = 3.5 \times 10^{-4} M_{\oplus}$.

5. DISCUSSION

Its reliable age determination makes HD21997 the oldest example for a gas-bearing debris disk. In many aspects it resembles the somewhat younger 49 Ceti. Both systems contain an A-type central star that produces energetic UV that could dissociate CO molecules in the vicinity of the star. 49 Ceti and HD21997 clearly stand out from our sample in terms of disk radius, and of harboring a large amount of relatively cold dust ($T_{\text{dust}} \leq 80$ K and $M_{\text{dust}} \sim 0.1 M_{\oplus}$). Note also that these two systems exhibit very similar $M_{\text{CO}}/M_{\text{dust}}$ ratios (~ 0.003). Based on their similarities, we speculate that HD21997 and 49 Ceti may be the first representatives of a so far undefined new class of relatively old ($\gtrsim 8$ Myr), gaseous dust disks.

Hughes et al. (2008) claim that the disk around 49 Ceti contains predominantly primordial gas and may represent the link between gas-rich primordial disks and gas-poor debris disks. It is a question whether HD21997 system may be of similar origin. The gas clearing process in primordial disks is expected to progress outwards due to photoevaporation driven by the central star (e.g., Alexander et al. 2006; Pascucci & Tachibana 2010), thus the last reservoir of gas will be the outermost part of the circumstellar disk. Indeed, HD21997 and 49 Ceti possess the largest disks and consequently have the longest expected survival time for gas in our sample (though the evaporation timescale also depends on the high energy flux of the central star). A confirmed primordial origin of the gas in the HD21997 system, would pose a serious question to the current paradigm since its age of ~ 30 Myr significantly exceeds both the model predictions for disk clearing and the ages of the oldest T Tauri-like or transitional gas disks in the literature (Kastner et al. 2008).

Primordial CO gas can survive only in the case of efficient shielding from the stellar/interstellar high-energy photons. We determined the stellar UV flux from the fitted ATLAS9 atmosphere model (see Section 4) and the UV component of the interstellar radiation field (ISRF) from Habing (1968). For each disk position, where the H_2 and CO column densities are provided by our model, we analyzed the shielding efficiency using the photodissociation model of Visser et al. (2009) for different N_{CO} and N_{H_2} pairs (shielding by dust grains is negligible in this tenuous disk). We found that no region in the disk is shielded enough to provide a CO lifetime longer than 500 yr. Adopting a lower scale height would lead to higher radial column densities but would not affect significantly the vertical column densities, thus the UV photons of the ISRF – which dominate the stellar UV flux almost everywhere in the disk – could efficiently photodissociate CO molecules. In the course of modeling we assumed that the gas and dust are sufficiently coupled leading to a common temperature, but in tenuous debris disks this may not be true (Kamp & van Zadelhoff 2001; Zagorovsky et al. 2010). Assuming a lower gas temperature similar to the measured excitation temperature would allow the existence of a larger amount of hydrogen gas. However, the gas is not likely to cool down to

such a low temperature all over the disk. Thus based on this result, as well as on the obtained H_2/CO ratio of ~ 1000 that is lower than expected for a primordial composition, the scenario of primordial origin of gas in HD21997 is unlikely.

Is it possible then, that the gas in this disk is of secondary origin, being continuously replenished from icy planetesimals? In this scenario the gas may have a very low H_2/CO ratio. Without the presence of a large amount of H_2 , shielding against UV photons is weak. Our modeling predicts CO photodissociation timescales of less than 500 years in the whole disk. In order to reproduce the observed CO mass of $\sim 3.5 \times 10^{-4} M_\oplus$, CO has to be released from solids with a rate of $> 7 \times 10^{-7} M_\oplus \text{yr}^{-1}$. Pure CO ice evaporates at temperatures above 18 K, thus it is volatile even far from the luminous central star, meaning that the surface of planetesimals is very likely already depleted in CO ice. However, CO ice can persist in deeper layers and/or can be trapped in mixed H_2O -CO ices even on the surface at temperatures below ~ 140 K. Destructive collisions between planetesimals can lead to the release of subsurface ices. In addition, frequent collisions of icy grains with smaller particles – mainly with β meteoroids – could produce a continuous flux of CO via vaporization. Photodesorption from solids can also significantly contribute to the gas production. Extrapolation of the current production rate for the last 20 Myr (assuming a primordial gas-rich disk phase in the first 10 Myr and a steady-state disk evolution afterwards) would yield a total of $> 14 M_\oplus$ of CO released from planetesimals/grains. Adopting a CO mass abundance of 10% in the planetesimals (see the composition

of the comet Hale-Bopp; Huebner & Benkhoff 1999), this scenario would require the complete destruction of more than $140 M_\oplus$ mass of planetesimals in the outer disk. It would significantly exceed the full initial dust content of a typical protoplanetary disk, making this steady-state scenario questionable. A more satisfactory explanation would be that the system is currently undergoing a phase of temporarily high CO production. The origin of this contemporaneous gas production might be imprinted in the spatial distribution of the gas and dust, and could be revealed with future interferometers.

Our results indicate that neither primordial origin nor steady secondary production can unequivocally explain the presence of CO gas in the disk of HD21997. An on-going temporarily high CO production may be more likely. Detection of other gas components and transitions with *Herschel* and *ALMA*, as well as the better characterization of the disk structure may lead to the deeper understanding of this enigmatic system and clarify whether 49 Ceti and HD21997 are the first examples of a so far less studied phase of disk evolution.

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TABLE 1
STELLAR/DISK PROPERTIES.

(1) ID	(2) Sel.	(3) SpT	(4) D (pc)	(5) Memb.	(6) v_{rad} (km s ⁻¹)	(7) T_{dust} (K)	(8) R_{dust} (AU)	(9) f_{dust} (10 ⁻⁴)	(10) Ref.	(11) M_{dust} (M_{\oplus})	(12) Ref.	(13) t_{on} (minute)	(14) I_{CO} (K km s ⁻¹)	(15) S_{CO} (Jy km s ⁻¹)	(16) M_{CO} (10 ⁻⁴ M_{\oplus})
HD 3670	1	F5V	(76)	ColA	+8.6	53	41	5.4	1	...		35.5	<0.050	<1.50	<0.85
HD 15115	1	F2	45	BPMG	+8.8	56	42	4.8	1	0.036	1	39.4	<0.045	<1.35	<0.28
HD 21997	2	A3IV/V	72	ColA	+17.3	64	63	5.9	5	0.14	1	255.3	0.109±0.014	3.28±0.53	1.79±0.32
HD 21997 ^a												115.9	0.078±0.014	2.29±0.47	4.9±1.1
HD 30447 ^b	1	F3V	80	ColA	+21.3	62	38	8.8	1	0.16	2	24.8	<0.050	<1.50	<1.01
HD 32297 ^b	2	A0V	112	...	+23.0	85	28	54.0	2	0.55	3	73.6	<0.027	<0.80	<1.25
HD 35841	1	F5V	(96)	ColA	+23.1	68	23	15.2	1	...		13.5	<0.065	<1.95	<1.96
HD 38207	2	F2V	(93)	ColA	+24.9	59	44 ^c	10.0	3	<0.28	4	22.4	<0.047	<1.41	<1.24
HD 106906	3	F5V	92	LCC	+11.1	90	20	14.0	4	...		24.2	<0.069	<2.08	<2.24
HD 110058	2	A0V	107	LCC	+5.0	130	11	25.0	2	<0.34	5	43.0	<0.051	<1.54	<2.90
HD 113766	3	F4V	123	LCC	-0.6	330	3	21.0	4	...		28.0	<0.055	<1.64	<8.75
HD 114082	3	F3V	85	LCC	+5.2	110	10	30.0	4	...		20.6	<0.066	<1.98	<2.11
HD 115600	3	F2IV/V	110	LCC	+4.7	120	10	16.0	4	...		24.0	<0.056	<1.67	<3.15
HD 117214	3	F6V	110	LCC	+7.2	110	11 ^c	7.0	4	...		10.8	<0.078	<2.33	<4.12
HD 121617	2	A1V	(120)	UCL	+13.6	105	28	48.0	5	<0.33	6	14.2	<0.070	<2.09	<4.24
HD 164249	2	F5V	48	BPMG	-0.2	70	27	10.0	2	<0.076	7	6.7	<0.129	<3.85	<0.99
HD 172555	2	A7V	29	BPMG	+2.0	320	2	8.1	2	...		26.2	<0.047	<1.39	<0.39
HD 181327	2	F6V	52	BPMG	+0.2	75	25	35.0	2	0.40	7	31.6	<0.037	<1.11	<0.34
HD 191089 ^b	2	F5V	52	BPMG	-5.8	95	15	14.0	2	0.022	4	17.1	<0.085	<2.55	<0.92
HD 192758	1	F0V	(62)	Argus	-11.1	56	52	5.4	1	...		9.8	<0.093	<2.78	<1.07
HD 221853 ^b	1	F0	68	LA	-4.2	83	22	7.9	1	...		3.4	<0.131	<3.91	<2.24
49 Ceti		A1V	59	...		80	60	7.9	2	0.074	8				2.60±0.54 ^d

NOTE. — Column 1: identification. Column 2: reference for the selection. 1—Moór et al. (2011), 2—Moór et al. (2006), 3—Chen et al. (2005). Column 3: spectral type. Column 4: distance. Parenthesis indicate photometric or kinematic distances, otherwise Hipparcos distances from van Leeuwen (2007) are used. Column 5: membership status. ColA: Columba Association; BPMG: β Pic moving group, LCC: Lower Centaurus Crux association, UCL: Upper Centaurus Lupus association, Argus: Argus moving group, LA: Local Association. Column 6: heliocentric radial velocity. Column 7: disk temperature. Column 8: disk radius. Column 9: fractional dust luminosity. Column 10: references for disk parameters. (1) Moór et al. (2011), (2) Rhee et al. (2007), (3) Hillenbrand et al. (2008), (4) Chen et al. (2005), (5) this work. Column 11: dust mass. Column 12: reference for submillimeter measurement that was used in the dust mass estimate. (1) Williams & Andrews (2006), (2) Nilsson et al. (2010), (3) Maness et al. (2008), (4) Roccatagliata et al. (2009), (5) Sylvester et al. (2001), (6) Sheret et al. (2004), (7) Nilsson et al. (2009), (8) Song et al. (2004). Column 13: on-source integration time. Column 14: line intensity for CO $J=3-2$. Intensity units are main-beam brightness temperature. Column 15: integrated line flux. Column 16: estimated mass of the CO gas.

^a Parameters from the $J=2-1$ line.

^b Kastner et al. (2010) reported the nondetection of CO(2-1) emission.

^c For those objects where our distance estimate differs from the literature value by >10%, the R_{dust} was rescaled according to our distance.

^d CO mass of 49 Ceti was derived using the CO(3-2) observation of Dent et al. (2005).

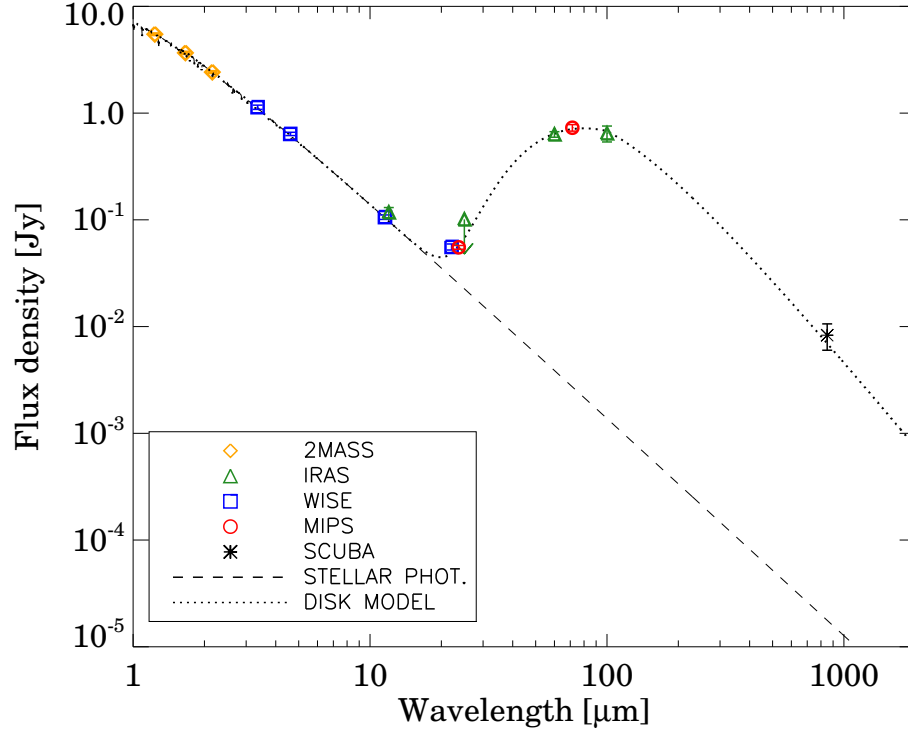


FIG. 1.— Spectral energy distribution of HD21997. Photometric data presented in this figure are color-corrected.

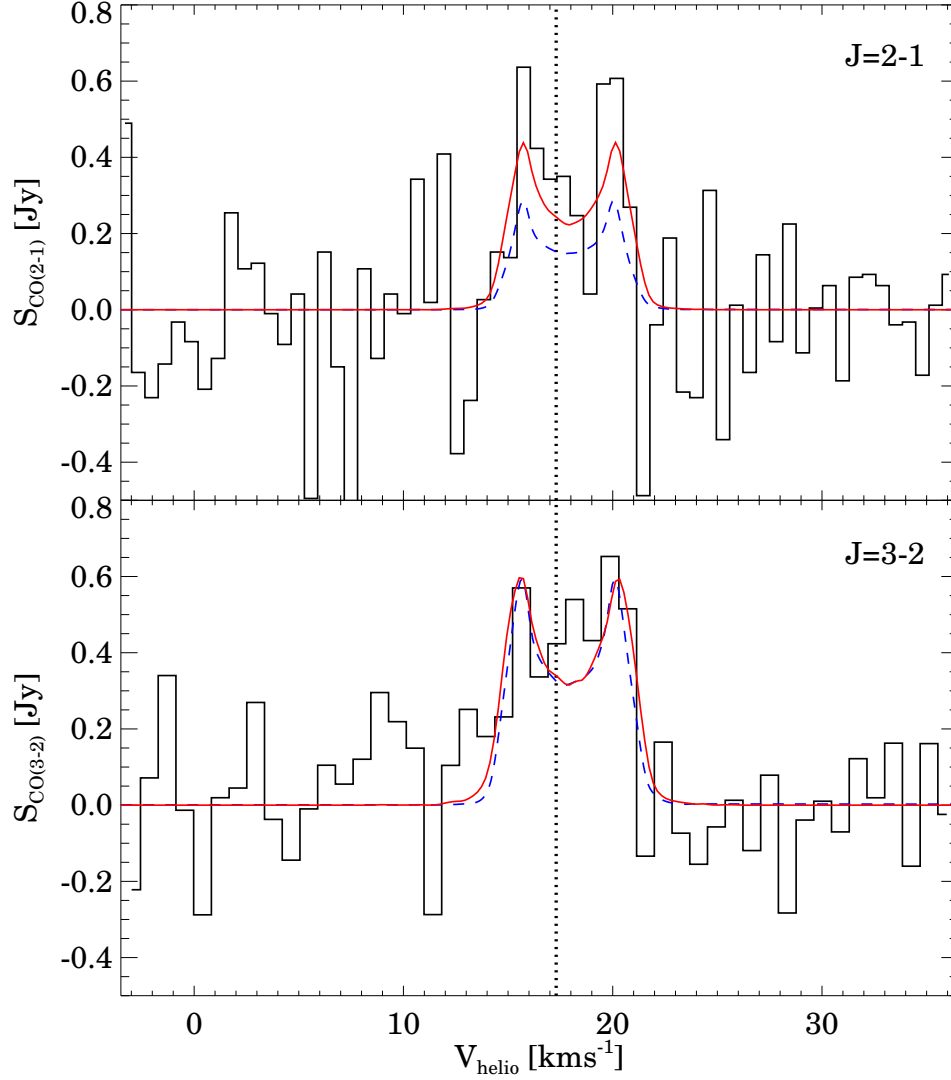


FIG. 2.— *CO* spectra of HD21997. The *CO*(3–2) spectrum is binned by a factor of two. Dotted line marks the radial velocity of the star. The dashed line (blue in online version) corresponds to a disk model with $H_2/CO=10^4$, the solid line (red in online version) to $H_2/CO=10^3$.

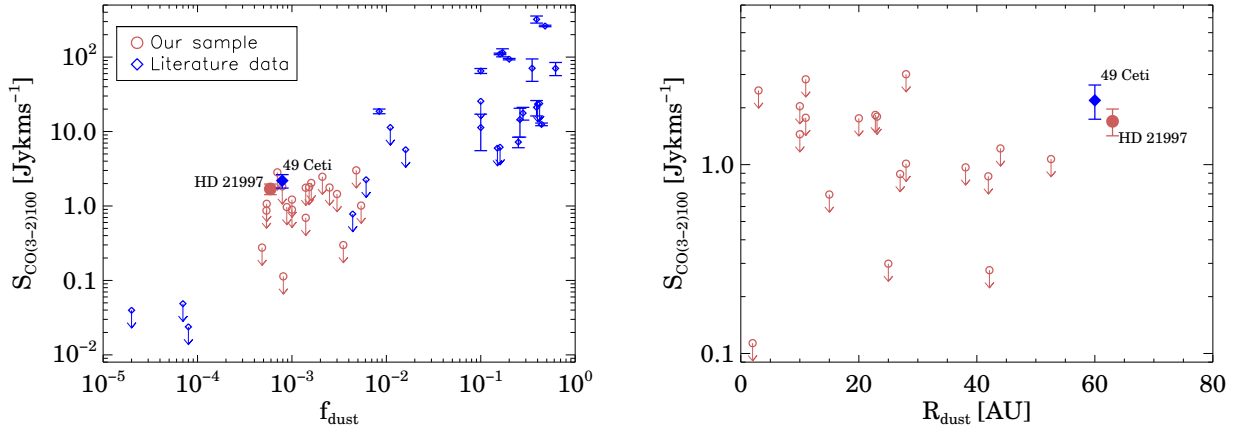


FIG. 3.— *Left panel*: integrated *CO*(3–2) fluxes or upper limits for our sample, and for protoplanetary/debris disks around A0-F6-type stars from literature data (Dent et al. 2005; Greaves et al. 2000a,b) normalized to 100 pc are plotted against fractional luminosities. 49 Ceti (Dent et al. 2005), and HD21997 are plotted with larger filled symbols. *Right panel*: integrated *CO*(3–2) fluxes for our sample and for 49 Ceti as a function of disk radii.